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Report

The Performance of Epoxy Coated Reinforcement- Experience of The Ontario Ministry of Transportation

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Abstract	The Ontario Ministry of Transportation has a mandate to specify cost-effective methods and materials for the construction and maintenance of provincial highway structures. In support of this mandate, the Bridge Durability Work Group initiated a performance evaluation of epoxy-coated reinforcement (ECR) in the Ontario bridge environment. Findings of the investigation, which are summarized in this report, strongly indicate that the long-term performance of the ECR is not likely to provide the corrosion resistance or associated maintenance free service life that was originally forecast. Several Ministry structures constructed with ECR have already been rehabilitated, before achieving even a 20-year service life. Today, the Ministry must develop and adopt strategies at the time of design for service life that far exceed the expectations of only a few years ago; typically, in accordance with the new Canadian Highway Bridge Design Code, the design life of new structures is anticipated to be 75 years. A significant body of research to date indicates that ECR can at best provide marginally longer service life than black reinforcement.
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Executive Summary

By the 1970's, it was clear that bridge deck deterioration due to corrosion had become a major problem for highway authorities in all areas of North America where deicing salts were used. Epoxy-coated reinforcement (ECR) was introduced in North America at this time as a means of providing a physical barrier to chlorides at the steel-concrete interface; research by the National Bureau of Science (now National Institute for Standards and Technology) and the Federal Highway Administration had indicated that coated bars performed well in salt-contaminated concrete and that epoxy-coated bars showed greatly reduced short-term corrosion rates, compared to black bars, in outdoor exposure plot installations. Highway authorities in North America rapidly adopted ECR and in a short time ECR became the primary corrosion protection strategy for concrete bridge decks in a number of jurisdictions that required deicing salt.

The Ontario Ministry of Transportation standardized their specifications for use of ECR in the top mat of bridge decks and in barrier walls in 1979, and by 1981 it was also specified for areas of substructure components exposed to deicing salts.

The initial developmental and field investigations of ECR performance were generally positive with regard to the protection afforded to embedded steel. However, beginning with the discovery that the splash zone region of substructure elements containing ECR in bridges in the Florida Keys exhibited corrosion-induced concrete cracking and spalling after only 6 years of exposure, questions pertaining to the corrosion resistance of ECR in concrete were raised. Over the next ten years the Ontario Ministry of Transportation initiated more stringent requirements for ECR quality, and carried out investigations of the condition of bridges built with ECR, in response to the concerns.

It is now generally accepted based on recent studies on the long-term performance of ECR and verified by the Ministry's own field experience, summarized in this report, that the corrosion resistance afforded by ECR is not likely to provide the maintenance-free service life that was originally forecast. This fact is demonstrated in that several Ministry structures constructed with ECR have already been rehabilitated before reaching a 20-year service life.

The ministry's corrosion protection strategy, including mandate for use of ECR, is continuing to evolve.

Background

Premature deterioration of highway bridge decks as a result of corrosion of the reinforcing steel was first identified as a serious problem in North America in the late 1960's. ECR was introduced in the 1970's to provide a physical barrier to chlorides at the concrete-steel interface. Although it found little acceptance in Europe and other parts of the world, ECR was soon adopted as the primary corrosion protection strategy by a number of jurisdictions in North America.

Fusion bonded epoxy-coating was identified as an effective method of corrosion protection in the early 1970's through research studies funded by the US Federal Highway Administration (FHWA) and the National Bureau of Standards (now the National Institute for Standards and Technology) (10, 1, 13). The first reported use of epoxy-coated reinforcement was in a bridge over the Schuylkill River near Philadelphia in 1973. For more than a decade, ECR was generally perceived effective in reducing or preventing chloride-induced corrosion in bridges and other concrete structures.

The first broadly circulated reports of corrosion of ECR occurred in 1986 in the substructure of bridges in the Florida Keys after only 4 – 6 years' service in a marine environment, in the tidal splash zone regions of piers. The very short time period for the corrosion distress to become apparent was attributed to the high temperatures, high humidity and high atmospheric chloride concentrations on the Florida coast. Isolated examples of corrosion of coated reinforcement were reported from about 1990 onwards although many field investigations reported good performance (8).

Since the Ontario Ministry of Transportation (MTO) had used ECR in bridge decks since 1979 and in substructure components since 1981 as a standard specification requirement, these reports of corrosion were a serious concern to the ministry. An MTO survey of field performance was undertaken in 1988 in response to the reports of poor performance of ECR in the Florida Keys. In view of the relatively short time that epoxy-coated reinforcement had been used in Ontario, it was decided to adopt a worst-case experimental design rather than a random survey. A deliberate attempt was made to locate those components having the highest chloride-ion contents at the level of the reinforcing steel. Since all MTO bridge decks are waterproofed, the investigation was limited to barrier walls and specifically to those barrier walls that had been in service the longest and were in locations subject to the greatest exposure to deicing salt. Two barrier walls built in 1979 with shallow cover and which exhibited cracking were investigated; one had been constructed with black steel, and one with epoxy-coated reinforcement. The investigation of the wall containing ECR (Eglinton Avenue) is discussed in detail below. In general, the study concluded that compared with black steel, the epoxy-coating had reduced corrosion activity substantially during the first nine years in service but while the initial indications were promising, long-term performance was uncertain (7).

In 1990, unexpected corrosion of ECR in precast concrete noise barriers was observed by the ministry; the panels were adjacent to one of the most heavily travelled highway sections in North America (Highway 401 at Keele Street) which is subject to deicing salt application. There was very low concrete cover over the steel, and the concrete was of relatively poor quality.

In 1992, a broader field and laboratory study was initiated by MTO to assess the performance of ECR. The program was initiated in response to ministry and Ontario industry concerns regarding the effectiveness of corrosion protection afforded by the ECR. The study included condition surveys of twelve structures built in the period 1978-1992, concentrating on barrier walls, and laboratory analysis of samples of ECR obtained from concrete cores from the structures, from construction sites and from a coating plant. The condition surveys included: assessment of the degree of reinforcement continuity, measurement of corrosion potentials using a copper-copper sulphate half cell, corrosion rate measurements using three electrode linear polarization, visual assessment of condition and removal of cores from representative areas. Subsequent laboratory work assessed the chloride content at the level of the reinforcement and the condition of the epoxy coating and the steel substrate, using standard testing techniques. The field surveys were carried out by ministry staff, with researchers at University of Toronto responsible for analysing the cores and for documenting the overall results of the study (6).

Overall, the study found that the bridges were in good condition and no delaminated concrete was identified in the structures studied. It was noted that, in some structures, chloride content at the level of the steel had exceeded the corrosion threshold. However, there was evidence of loss of coating adhesion from the steel substrate after approximately 10 years of exposure. The loss of adhesion was seen on ECR in both chloride-contaminated and chloride-free concrete environments. The steel substrate of bars with debonded epoxy was clean and shiny in chloride-free concrete, but was visibly corroded in concrete where chloride levels had exceeded the corrosion threshold.

In 1993, due primarily to the findings of this study, several meetings were held between representatives of MTO and the epoxy-coating industry. The main purpose of the meetings was to discuss mutual concern regarding the performance and quality of the ECR. As a result of the meetings, MTO specifications for ECR were upgraded to improve coating adhesion by specifying a chromate treatment prior to coating, shorten unprotected storage time on site, reduce allowable damage to coating, require repair of all visible damage to ECR prior to placement of concrete, and make mandatory the use of plastic-coated vibrators for consolidation of concrete containing ECR.

In 1996, performance problems with ECR were discovered in two MTO structures through accidental exposure; barrier walls on two different structures were struck by out-of-control vehicles, exposing the reinforcement. On one structure (Highway 7, Peterborough) the exposed ECR was found to be actively corroding (Figures 1 and 2). On the other structure (Queen Elizabeth Way, Burlington Bay Skyway) no corrosion was observed, however the epoxy showed little or no adhesion to the reinforcement (Figures 3, 4 and 5).

During repair work (expansion joint replacement) in the expansion joint end dams of five bridges, carried out during this same time period, it was observed that ECR in all five end dams was experiencing corrosion. It should be noted that, like barrier walls, end dams on ministry structures have no waterproofing or other protective barrier to prevent ingress of chlorides and moisture, and so are subject to a more aggressive environment than the bridge deck.

Since two out of two bridges identified by accidental exposure and a significant number of bridges undergoing routine rehabilitation activities were found to display problems with ECR, either loss of coating adhesion or actual corrosion, the ministry decided to investigate more aggressively the performance of ECR.

In 1997 the ministry initiated the detailed investigation of the barrier walls of five highway bridges constructed in Ontario in 1979, to assess the effectiveness of the epoxy coating in preventing chloride-induced corrosion. From this investigation, it became clear that the epoxy coating was not effective in protecting reinforcing steel from corrosion over the long term. This was visually evident as significant areas of some of the concrete barrier walls showed significant corrosion-induced delamination and spalling. Figures 6 and 7 show delaminations, determined by sounding, marked on the barrier wall of Highway 17's Madawaska River Bridge (Site 29-191), built in 1979 with ECR. Analysis of cores removed from the structures verified that, where chloride levels exceeded threshold levels, corrosion of the ECR was taking place. Based on the structures studied, it appeared that while the epoxy coating may have delayed the onset of corrosion somewhat, it did not prevent corrosion from occurring. Findings were summarized in an internal report (9).

The purpose of the remainder of this paper is to provide an update on the ministry's investigations since the 1997 barrier wall study, and to document the significant findings with respect to ECR performance.

Field Observations and Their Significance – (MTO Experience Post 1997)

Field Performance of ECR - Update

The following represents the most significant recent findings and observations by MTO on the performance of ECR, based on both field studies and interaction with other jurisdictions.

(A) Performance of ECR on the Perley Bridge

In 1998, a unique opportunity arose to study an Ontario bridge deck constructed with ECR in both top and bottom deck mats; during discussions with industry, it had been suggested that MTO's poor experience with ECR might be related to the MTO policy of using coated steel in the top mat only. The Perley Bridge, a federally owned structure, was built in 1931, spanning the Ottawa River between Hawkesbury Ontario and Grenville Quebec. A study commissioned in 1985 by Public Works Canada concluded that the concrete deck of the Perley Bridge was in an advanced state of deterioration and exhibited extensive areas of corrosion. In December 1998, a new Perley Bridge was completed adjacent to the first and opened to traffic. The subsequent demolition of the earlier structure allowed MTO, with the cooperation of Public Works Canada, to investigate the performance of deteriorated spans of the old bridge.

Span 17 had a history that made its investigation particularly useful. In 1979 the asphalt surface of Span 17 was removed and a new concrete deck was placed using the existing steel decking as formwork. Span 17 was rebuilt with both mats of reinforcement epoxy-coated and the deck was left with the concrete surface exposed. All other spans of the Perley Bridge were built with black reinforcement. The repair and maintenance history for the next 20 years showed that corrosion occurred in one of the two lanes of Span 17 soon after it was rehabilitated. In 1998 a condition survey was conducted by the MTO that included mapping the patched and spalled areas of Span 17. The depth of concrete cover to the steel was measured using a cover meter. Cores were taken from both patched and original areas of the deck. Photographs were taken of the cores to document the extent of deterioration of the ECR. Figures 8,9,10 and 11 show evidence of ECR corrosion in cores from the westbound lane. It was clear that the two lanes (eastbound and westbound) had experienced vastly different corrosion behaviour, although both contained epoxy coated steel of apparently equal quality.

To investigate those corrosion problems, MTO commissioned an independent investigation, carried out jointly by the U. S. Department of Energy, Albany Research

Center and John S. Tinnea and Associates, to determine the extent and cause of damage to the Span 17 deck and to identify the reasons for the different corrosion behaviour.

Two full-depth slabs cut from Span 17 of the Perley Bridge were delivered to the Albany Research Centre for examination. Slab M1 was cut from the eastbound lane, in which no patches were recorded during the 20-year history of Span 17. Slab M3 was cut from the westbound lane of the bridge, which had been patched extensively, over approximately 40% of its area, beginning early in its life. Measurements made by MTO on site indicated that the concrete cover on the eastbound lane was almost twice that of the westbound lane.

A wide variety of destructive and non-destructive techniques were used by the investigators to examine Slabs M1 and M3; measurements were made to determine the properties of the epoxy coating, the steel reinforcing bar, and the concrete. Detailed results are documented in (2).

Results of Investigation

Testing indicated that the original concrete and the patch concrete used to rehabilitate the span were of good quality, in terms of compressive strength and resistance to chloride ion penetration. There was no evidence that the installed ECR failed to meet the applicable standard at the time of installation; for example, the blast profile for the steel reinforcing bar was measured and determined to be adequate.

Conclusions of the investigators were that the epoxy-coating adhesion deteriorated in service and the damage to the coating increased, resulting in increasing exposure of the steel bar to chlorides. While coating adhesion was found to be good to fair over much of the reinforcing steel, there were isolated areas where it was poor or did not exist. Steel reinforcing bar half-cell potential measurements indicated there was a high probability of corrosion of the ECR in both M1 and M3. However, the ECR in Slab M3 exhibited 50% more rusting than the ECR in Slab M1

The first recorded indication that the Perley Bridge was in distress, based on the structural inspection records, was in 1986 (westbound lane section M3) and the first known patches to the Span 17 deck were done in 1990. Using 1986 as the date that corrosion damage was first noticed, the "worst-case" estimate of time for corrosion to cause damage to the deck was 7 years from the date the span was rebuilt; a "best-case" estimate of time to corrosion is obtained if the date of first repair in 1990 is used. In other words, corrosion of the ECR in the deck was initiated and progressed to the extent that damage to the concrete was noticed, in a time period of between 7 and 11 years.

There was inadequate (low) cover depth relative to the top mat of steel reinforcing bars for slab M3; the researchers concluded that this resulted in chloride levels at the depth of the top mat in M3 that exceeded the corrosion threshold for black steel reinforcing bar, within 2.7 years of deck installation. They suggested corrosion propagation time, based on work by Sagues, of 3.5 years for bare steel reinforcing bars. Adding these two figures (initiation time and propagation time) the total time for the first appearance of corrosion

in the slab, if black steel were used or if the epoxy provided no protection at all) would be expected to be in the area of 6.2 years.

In summary the investigation concluded that the epoxy coating used in the westbound lane of the Perley Bridge deck in Span 17 provided only 1 to 5 years of additional protection over bare steel reinforcing bar, in terms of corrosion resistance.

Because of greater cover depth, the corrosion threshold for the top mat of bars in M1 was estimated to have been reached only after 15.4 years. This resulted in a significantly extended time to corrosion and consequently, appearance of corrosion damage in Slab M1 was delayed until about the time of the bridge replacement.

(B) Performance of ECR on the Eglinton Avenue Bridge

The Eglinton Avenue Bridge over Highway 403, built in 1979, is of particular interest because it was included in condition investigations conducted by MTO in 1988, 1992, 1997 and 1998. Several evaluation procedures were used, including determination of chloride profiles, continuity of reinforcement, half-cell potential measurements, rate of corrosion and the condition of the steel and of the epoxy coating. The results of the 1988 investigation on the walls of this structure concluded that there was no evidence of corrosion on the coated bars. There was evidence of poor bond between the epoxy and the ribs on several bars, but the coating was well bonded to the steel between the ribs. A similar barrier wall also constructed in 1979 but with uncoated reinforcement, was also studied for purposes of comparison. The 1988 study concluded that, compared with black steel, the epoxy coating had reduced corrosion activity substantially during the first 9 years in service but, while the initial indications were promising, the long-term performance was uncertain (7).

In 1992, Eglinton Avenue was studied along with 11 other bridges built in the period 1978 – 1992, and conclusions of the study, noted previously, were that the bridges exhibited no delaminations but there was evidence of loss of coating adhesion on ECR in chloride free concrete and also in concrete where the chloride corrosion threshold was exceeded. Findings from the investigation (6) of the Eglinton Avenue structure indicated that the chloride corrosion threshold at the level of the reinforcement was above the level required to initiate corrosion for black reinforcement. Resistance measured between the reinforcement exposed at cored holes was between 760 and 1600 ohms (measured using an AC ohmmeter). The core holes were widely spaced along the wall and resistance between them would be dependent on the degree of continuity (i.e. direct contact) of the substrate steel. Comparatively, these values are low and are an indication that the ECR coating was not providing as effective a barrier as expected (for new ECR construction, values over 5000 ohms would typically be expected). This was considered to be an indication that the ECR was deteriorating with time.

In 1997 a 50-metre section of the barrier wall at the southwest corner of the Eglinton Avenue Bridge was visually assessed and sounded for delaminations, and approximately 7% of the surface area was found to be delaminated. It appeared that the delaminations had appeared since the 1992 investigation, corresponding to an average delamination

growth rate of approximately 1.4 % per year. In Figure 13 the wall section can be seen with the delaminated areas marked on the surface. Figure 14 shows the type of corrosion seen on the ECR in cores removed from delaminated areas of the structure (at the edges of the photograph it can be seen that the colour of the epoxy-coating in this structure was brown rather than green; this colour was used for a very brief period of time in Ontario). An internal report (9) documented the extent of delaminations and corrosion of the ECR found on the bridge.

The same barrier wall was again sounded for delaminations in 1998. It was found that some of the previous delaminations had increased in size, while some new delaminations had appeared. Overall, delaminated concrete covered approximately 9% of the surface area investigated, a 2% increase from the previous year. Based on the ministry's past experience, the delamination progression on this bridge, once delaminations were detected, appears to be consistent with, and typical of, black reinforcement in a similarly corrosive environment.

(C) Performance of ECR on the Humber River Bridge

The Humber River Bridge (Highway 427 – Site Number 37-633) was built in 1982; this bridge carries heavy urban traffic and is located in northwest Toronto. The bridge deck was waterproofed and paved at the time of construction. In 1998 the bridge was widened as part of an upgrading project to increase the traffic capacity of the highway. In the course of widening the bridge, the barrier wall and sidewalk were removed, and the end portions of the epoxy-coated transverse bars in the bridge deck were exposed. The bars were exposed with some care since they would remain in place to provide a structural link to the new portion of the structure. This offered the ministry a unique opportunity to examine the condition and performance of the coated reinforcement.

There were many locations of visible deterioration of the epoxy coating. These included areas with total loss of adhesion of the epoxy coating to the steel, brittleness of the epoxy-coating and numerous defects and bare areas within the epoxy coating. It should be noted that this was not damage caused by the concrete removal operations. Figure 14 shows the exposed ECR after removal of the surrounding concrete; Figures 15, 16 and 17 illustrate the extent of deterioration of the epoxy coating and condition of the steel on this site.

The fact that most of the reinforcement was corroding but was not in a more advanced state of deterioration was probably due to the effectiveness of the bridge deck waterproofing membrane and the concrete cover in providing protection from chloride ingress. (Along with waterproofing and paving of all bridge decks, it is standard ministry practice to specify a concrete cover of 70 ± 20mm.).

The previous ministry experiences with deteriorating ECR and related corrosion had been restricted to barrier walls and end dam areas (where no protective waterproofing membrane is applied), and the poor condition of the ECR in the bridge deck at this site came as a surprise.

It had been assumed that the coating would be in sound condition and the contract had originally required only that any areas of damage on the ECR be repaired before placement of new concrete; the extent of coating and steel deterioration made this approach impractical. Instead, abrasive blasting was used to remove any remaining coating on the steel and to clean the steel surface before new concrete was placed, to ensure a sound bond between the steel and concrete.

(D) Performance of ECR on the Garden City Skyway

The Garden City Skyway (Queen Elizabeth Way, Site 18-111) is a high level bridge 2200m long and 21m wide constructed in 1963 over the Welland Canal. Due to chloride contamination over the years, significant corrosion-induced deterioration had occurred. Since original construction, partial rehabilitation of the superstructure had been carried out including construction of new barrier walls with ECR in 1981. In 2002 a major rehabilitation was carried out on the structure, including repair of the deck and barrier walls. Epoxy-coated steel removed from the barrier walls was examined; some areas of barrier wall had very little cover, resulting in relatively rapid penetration of chloride to the level of the steel. Figures 18 and 19 illustrate an unusual type of corrosion observed; the bars appear to show initiation and progression of corrosion beneath the coating, while the coating remained relatively intact (but disbonded from the steel). The corrosion products are distributed along a length of bar in an even manner, rather than concentrated at a point. Until recently the idea that corrosion could initiate beneath disbonded epoxy was considered somewhat speculative. However observations on the steel from the Skyway would appear to confirm this affect and this is significant to MTO in that this is the first documented case of such corrosion on a ministry bridge.

Related Corrosion Initiation and Propagation Issues

There is general agreement that the critical chloride concentration necessary to initiate corrosion at flaws in the ECR is the same as that for black steel (2, 4) and, common sense would argue that it should be because the steel exposed at the flaws in the epoxy-coating is black steel. The time taken for chlorides to reach that critical concentration at the level of the bar is determined by the depth of cover and the quality of the concrete, and is independent of the type of rebar. Thus, the effect of cover depth and concrete quality on the initiation of corrosion would be the same for epoxy-coated steel and for black steel reinforcement.

On the other hand, there is no unanimity concerning the rate of corrosion once initiated. Again, common sense would suggest that the average corrosion rate should be lower than that of black steel because it is limited to the flaws and adjacent areas. Some argue, however, that the local rate of corrosion is higher because the epoxy coating allows crevice corrosion to take place and this is known to occur at higher rates than normal corrosion. The lack of consensus may be due to the differences in environmental conditions at different sites, the indications being that rapid crevice corrosion could be more prevalent in hot marine climates (11). The "small anode-large cathode" theory also suggests corrosion could be accelerated (15).

Further, researchers have suggested that active corrosion will eventually occur in the disbonded regions of the epoxy coating even in the absence of chloride ions. Weyers (15) proposed that under such circumstances, the lack of oxygen and the neutral or acidic solutions within the epoxy would allow the corrosion to take place without the production of voluminous corrosion products and the associated cracking and spalling of the cover.

The cores from the Garden City Skyway would appear to confirm the proposed mechanism.

(E) Performance of ECR on the CNR Overhead Bridge

In 2000, major rehabilitation of a series of structures near North Bay Ontario was carried out; barrier walls constructed with ECR were repaired as part of the project. One structure, the CNR Overhead Bridge (Site 43-105) demonstrated significant and extensive damage of the concrete; Figure 20 shows a drawing indicating the locations of delamination and spalling of the structure walls prior to repair. Most of the concrete damage occurred near the top of the wall where a heavy concentration of chloride ions would be expected. This barrier wall was not yet 20 years old at the time of rehabilitation. Based on the significant number of delaminations found on the barrier wall, it can be concluded that the ECR was not effective in preventing corrosion of the reinforcement over the long term.

(F) Condition of ECR Exposed by Vehicle Damage

As previously mentioned, early performance problems with ECR were first observed in MTO structures through accidental exposure when in 1996, two different structures were struck by out-of-control vehicles, exposing the reinforcement.

In 2003, two additional structures (Sites 37- 984 and 24-465) were struck by vehicles, causing damage to the concrete and exposing the ECR. At Site 37-984 the exposed ECR was found to be in poor condition. An examination of the entire barrier wall found that large areas of the wall were cracked and delaminated. The delaminations and cracks were related to corrosion of the reinforcement.

At Site 24-465 the vehicle collision damaged the concrete. Once the loose concrete was removed, it was discovered that the reinforcement had large areas of epoxy missing; this occurred because over time the epoxy had lost adhesion with the steel to the point that the epoxy bond with the concrete was greater than with the reinforcement. When the concrete was removed the epoxy was cleanly removed from the reinforcement.

The two incidents, in addition to the 1996 collisions, were considered significant in that these totally random events all four of the walls were found to contain actively corroding bars or bars where the coating had disbonded. This suggests that the loss of bond is a widespread phenomenon, not confined to any particular age of structure or type of steel. When chloride is present in sufficient quantity to initiate corrosion, it proceeds.

Sources of Additional Information and Consideration on the Use of ECR

(A) Significance of Job Site Quality of ECR.

A recent study completed by Hartt (5), who assessed a total of 76 salt contaminated concrete slabs that contained ECR and were exposed outdoors for over six years, concluded that:

(a) Coating defect density was the predominant parameter that affected ECR performance.

(b) The number of coating defects increases with exposure time in concrete with the rate of this increase being constant and proportional to the initial defect density.

(c) Coating disbondment occurs and proceeds outward from coating defects.

These findings are supported by a study of the Florida Keys bridges performed by Sagues (11). In this study, Sagues and co-workers developed service life models to fit the findings on the Florida Keys bridges and concluded that the quality of the coating controls the propagation phase of the corrosion process on epoxy-coated rebars. The study to evaluate the failure of a section of the Perley Bridge deck (2) also concluded that the poor quality of the coating contributed to the early failure of a section of Span 17.

It can be concluded, based on the above, the better the quality of the coating, the longer it takes to deve'op corrosion-induced damage.

Ensuring that quality of coating is maintained throughout the ECR manufacturing, transportation, fabrication and installation processes is recognized as critical; ministry specifications were tightened to address specific concerns however lack of adherence to the specification requirements continues to be a problem reported by MTO field personnel. The ministry continues to experience quality issues with the steel that is used in our structures; Figures 21,22,23 and 24 show examples of the quality of the ECR found on a recent new construction project. As can be seen from the figures, the coating can be severely damaged prior to placement of ECR on a structure, and vigilant inspection is required to ensure that damaged material is replaced or repaired, not placed in the work. (In 1997, another Ontario jurisdiction, City of Toronto, discontinued use of ECR based on the difficulty of quality assurance.) As previously mentioned, the number of coating defects increases with exposure time, with the rate of this increase being constant and proportional to the initial defect density.

(B) Repair of Structures Constructed with ECR

The primary goal of a research project recently completed by the National Cooperative Highway Research Program Project 010-37C (12) was "to address the anticipated need for premature repair and rehabilitation of concrete bridge elements containing epoxy-coated rebar (ECR)".

The report concludes "although concrete damage from ECR corrosion is not presently widespread, this corrosion control alternative is not likely to provide the relatively maintenance – free service life that was forecast earlier and that intensive repairs and rehabilitations will ultimately be required during the anticipated service life of many structures".

The report also states that cathodic protection is now generally recognized as one method that can be used for control of ongoing corrosion of bare steel in chloride contaminated concrete. However, ECR presents unique repair challenges in that treatments such as cathodic protection and electrochemical chloride extraction may be compromised or ineffective. For example, the usefulness of the techniques may be limited because of the anticipated lack of electrical continuity between ECR bars, potential for coating disbondment during application of current, and potential for lack of current flow to steel beneath disbonded but intact areas of coating.

(C) MTO Structures Constructed with ECR Repaired to Date

The MTO first used ECR in bridge decks and barrier walls in 1979 and a number of the early structures have now undergone repairs, as have those of other Ontario jurisdictions. Table 1 presents a list of structures that have suffered deterioration due to corrosion and have been repaired.

Table 1

Structures Constructed with ECR Where Corrosion Damage has been repaired

Name	Location	MTO Site No. Installation	Date of ECR
Madawaska River Bridge	Hwy 17	29-191	1979
Modeland	Hwy 40	14-279	1980
Perley Bridge	Hawkesbury, Ont	N/A	1979
Garden City Skyway	Q.E.W.	18-111	1981
CNR Bridge	Hwy 11	43-105	1980
Birche's River	Hwy 11	43-199N	1981
Birche's River	Hwy 11	43-199S	1981
Lavase River NB	Hwy 11	43-200N	1981
Lavase River SB	Hwy 11	43-200S	1981

The majority of repairs to date have been largely limited to barrier walls. The use of improved waterproofing materials on bridge decks has reduced their vulnerability to corrosion damage, but no such supplementary corrosion protection is present in components such as barrier walls, expansion joint dams or sidewalks.

A recent consultant study, carried out for the Ministry and reported in (3) evaluated the field performance of ECR in 12 waterproofed bridge decks. A conclusion of the report was that generally the chloride content of the concrete had not yet reached the corrosion threshold level at the depth of the reinforcement; consequently, corrosion would not be expected. This fact was further demonstrated by the observation that negligible performance variations were found between the decks with epoxy coated steel in the top mat, and one which included black steel in the top mat (i.e. the black steel in the top mat reinforcement was also in a passive non-corroding state). The report further concluded that, based on the findings of the assignment "it appears that the "belt and suspenders" approach adopted after 1978, consisting of increased cover, improved concrete quality and improved waterproofing materials, has provided an effective corrosion protection system for over 20 years".

(D) Corrosion Protection Strategies for Ministry Bridges

Based on the evidence of premature reinforcement corrosion in some of the structures in which ECR was used, and other issues such as job site quality control, the ministry decided in 1998 to restrict the future use of ECR. However, due in large part to a critical response from the epoxy-coated steel industry, the Ministry ban on ECR was rescinded the same year.

The conflicting research findings cited by industry regarding the performance of ECR led the ministry to convene an expert task force consisting of representatives from the ministry and leading proponents of both "pro" and "con" epoxy-coated reinforcement camps. However the discussions of the task force were not conclusive and no direction was provided to the Ministry.

This turn of events led the ministry to hire a team of independent experts in 1999, with the aim of determining the most cost effective corrosion protection strategies for the province's concrete highway structures. A review would be undertaken to determine the most cost-effective use of corrosion protection strategies in concrete highway structures, based upon capital and rehabilitation costs, road user costs and the service life of structures. The review would be conducted by a team of Ontario academics and engineering consultants, directed by a steering committee of ministry staff and industry representatives from both the steel and concrete industries. Multiple options for corrosion protection would be studied, including both alternative reinforcement types and high performance concrete, using an approach based on life cycle costing.

In July 2000 the principal investigators for the project, Professors C. Hansson and R. Haas of the University of Waterloo, provided the final report "Corrosion Protection Strategies for Ministry Bridges" (4) to the ministry. The further use of ECR by MTO was not recommended, based on both technical and life cycle cost analyses.

Among the consultants' specific recommendations were the following:

(i) "When the lack of any suitable repair methods and non-destructive evaluation methods for ECR is taken into account, it is clear that an extra service life of only about five years does not warrant the use of ECR and it must be concluded that ECR will not be viable for a design life of 75 years".

(ii) "On the basis of technical merit, the use of stainless steel is strongly recommended, particularly for those components exposed to severe conditions, including expansion joint dams, barrier walls and sidewalks."

(iii) "The use of high performance concrete as defined by MTO, (OPSS 904 HPC, May 1998) is recommended for components exposed to severe conditions."

Since the submission of the above report, to the present day, the ministry's corrosion protection strategy has continued to evolve. Use of stainless steel reinforcement is now the norm for those structure components with the most severe exposure (barrier walls, expansion joint dams, and sidewalks on structures), in most new construction. In addition, significant use of high performance concrete to enhance structure durability has been made in some areas of the province. Balancing the increased cost of corrosion protection, against the value obtained, remains a challenge for the ministry.

Cost and availability of ECR have also become an issue; due to market changes, the ministry is essentially supplied by a single source of epoxy-coated steel. Prices for epoxy coated steel have also risen relative to stainless steel due to steel supply issues with the ratio between cost of ECR and stainless dropping significantly since use of stainless steel was initiated by the ministry.

(E) A Methodology for Conducting Surveys on Structures Constructed with ECR

Currently MTO condition surveys involve carrying out a detailed visual inspection of the structure as well as a condition investigation (both destructive and non-destructive) including a half-cell potential survey to assess the corrosion condition of the steel. MTO inputs the information obtained from the condition survey into a process to establish the method of rehabilitation for the structure. Both the condition survey protocol and the decision matrix process were developed based on experience with black steel reinforcement.

Since the epoxy resin is not electrically conductive, half-cell potential measurements on epoxy-coated steel do not provide useful information. Conventional condition surveys conducted on structures containing ECR provide limited information and use to the Ministry. It was recognized that a new approach for condition assessment of structures built with ECR is required. This is an issue not only for MTO, but also for many transportation agencies.

A research project (Special Project Q9000129) was initiated by MTO and carried out by a team consisting of Trow Consulting Engineers, Concorr Inc., and Cement and Concrete Studies, with the primary purpose of developing a new methodology for condition surveys on structures constructed with epoxy-coated reinforcement. A recommended protocol was developed, which is reported in (14)

The recommended protocol consists of a two-phase investigation process, with the first phase to be carried out after a minimum of 15-20 years of service. In the Phase One investigation, standardized test methods are utilized to collect data on the condition of the steel and concrete, that are then input to a service life prediction model to predict a time-to-corrosion and service life for the structure. The use of bridge deck service life prediction formula for both the corrosion initiation period and the propagation period (to reach a specified level of structural damage), represent a new approach that takes into account the influence of the waterproofing membrane on chloride penetration and state-of-the-art knowledge with respect to the corrosion performance of epoxy-coated bars in chloride-contaminated concrete. The findings of the Phase One investigation are used to determine the timing of the second phase of investigation, based on the anticipated time at which significant damage to the structure will have occurred. The primary goal of this Phase Two survey is to collect sufficient data to support the rehabilitation process.

A full description of the test methods proposed for use, and the method of service life prediction, is included in the report. The recommended protocol takes a rigorous approach which is expected to yield much more useful information than is currently available to the ministry, but this comes at a higher cost than a conventional survey.

Field trails of the new protocol are necessary in order to refine the process for future ministry use, as well to validate the overall approach. A Phase One condition survey was carried out on selected sections of the Burlington Bay Skyway in the fall of 2004, for this purpose. Data from this survey will be used to fine-tune the protocol with the intent of improving the cost effectiveness of future condition surveys

Conclusions

1. Based on the findings of field studies described in this report, which include a significant number of MTO bridges documented with poor performance of ECR, it can be concluded that the corrosion protection provided by ECR has not been as originally intended or expected.

2. The fact that several MTO bridges originally built with ECR have already been rehabilitated prior to achieving a 20-year service life, is cause for concern.

3. The number of structures across the province which have exhibited deterioration is a strong indicator of the widespread nature of ECR corrosion. The deterioration is not specific to a particular supplier of steel, to a specific area of the province, or to unusual exposure conditions.

4. Epoxy-coated steel does not provide effective long term corrosion protection in the Ontario bridge environment.

5. It is acknowledged that the use of ECR will increase the service life of structures over those constructed with bare steel. However this increase in service life is difficult to quantify. Work completed for the ministry by the U.S. Department of Energy (Albany Research Centre) concluded that "the epoxy coating used on the west lane of the Perley Bridge deck in Span 17 provided only 1 to 5 years of additional corrosion protection over bare steel reinforcing bars." It should be noted that both mats of steel on Span 17 were epoxy coated.

6. Since the Ministry's initial ban of ECR in 1998 no new information has become available which would either improve its observed performance or indicate that the ministry's experience is due to unique conditions. A number of jurisdictions have now discontinued use of ECR.

7. Because the use of ECR severely limits the investigative techniques and repair methods that can be used, new approaches to condition assessment and repairs will be needed for the large population of Ontario structures containing ECR.

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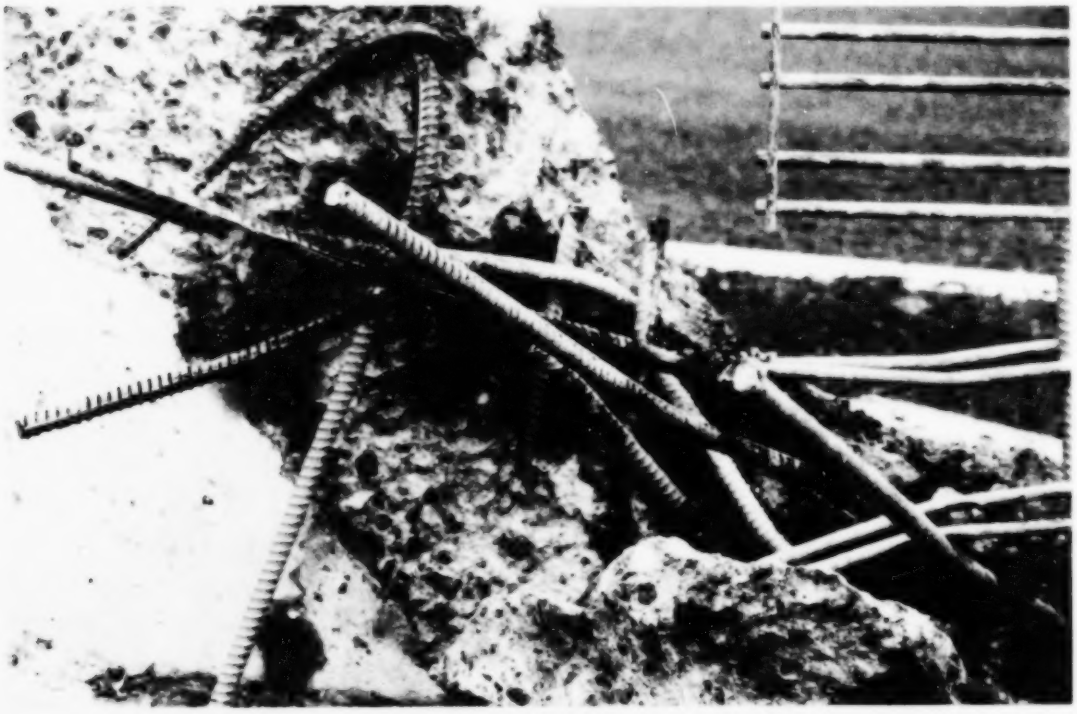

Figure 1 Accidental exposure of ECR, 1996, Peterborough (Site 26-173)

Figure 2 Accidental exposure of ECR, 1996, Peterborough (Site 26-173)

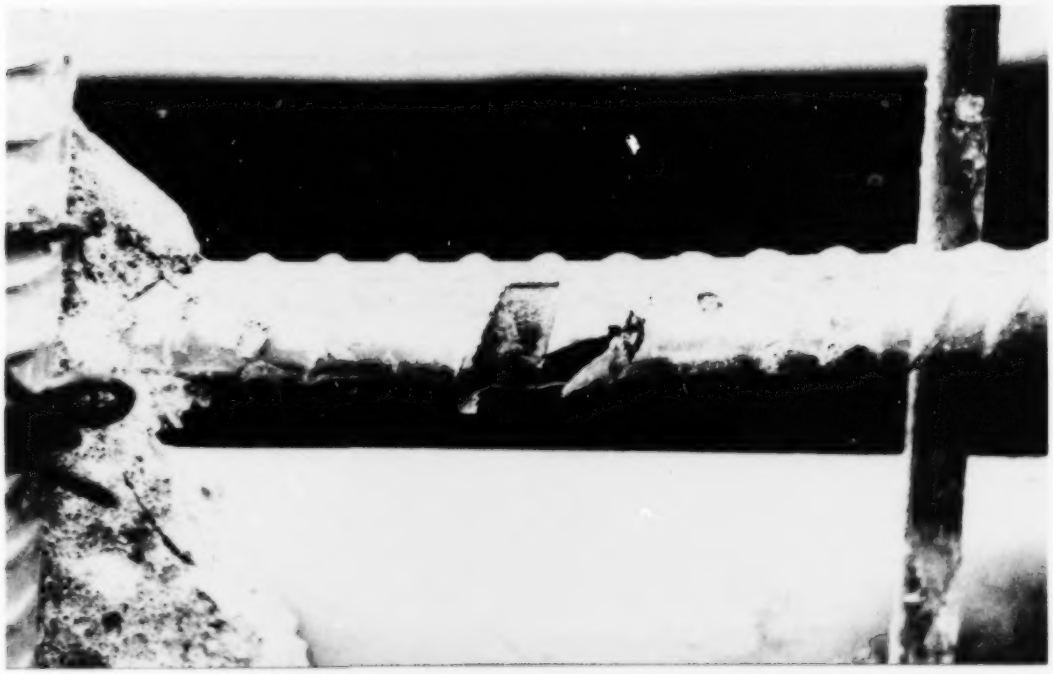

Figure 3 Accidental exposure of ECR, 1997, Burlington Bay Skyway (Site 36-060)

Figure 4 Accidental exposure of ECR, 1997, Burlington Bay Skyway (Site 36-060)

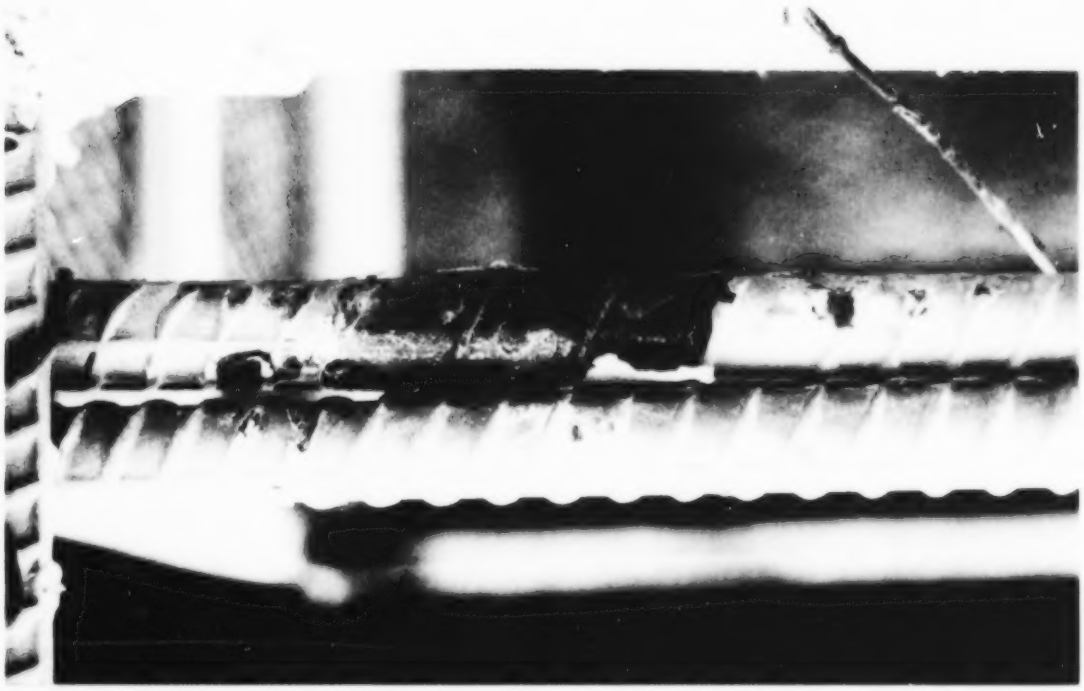

Figure 5 Accidental exposure of ECR, 1997, Burlington Bay Skyway (Site 36-060)

Figure 6 Corrosion-induced delamination of Madawaska River Bridge (Site 29-191)

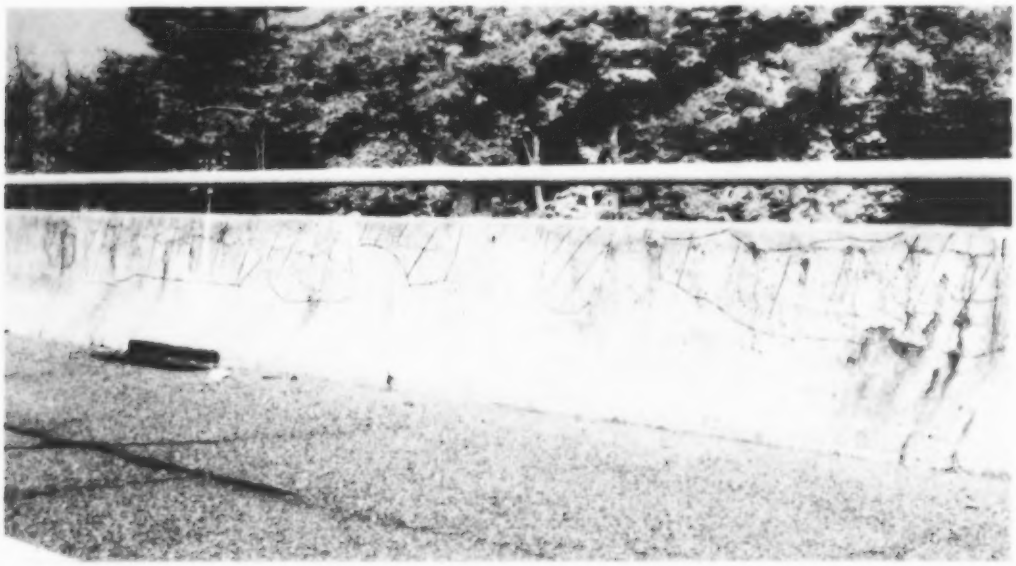

Figure 7 Corrosion-induced delamination on Madawaska River Bridge (Site 29-191)

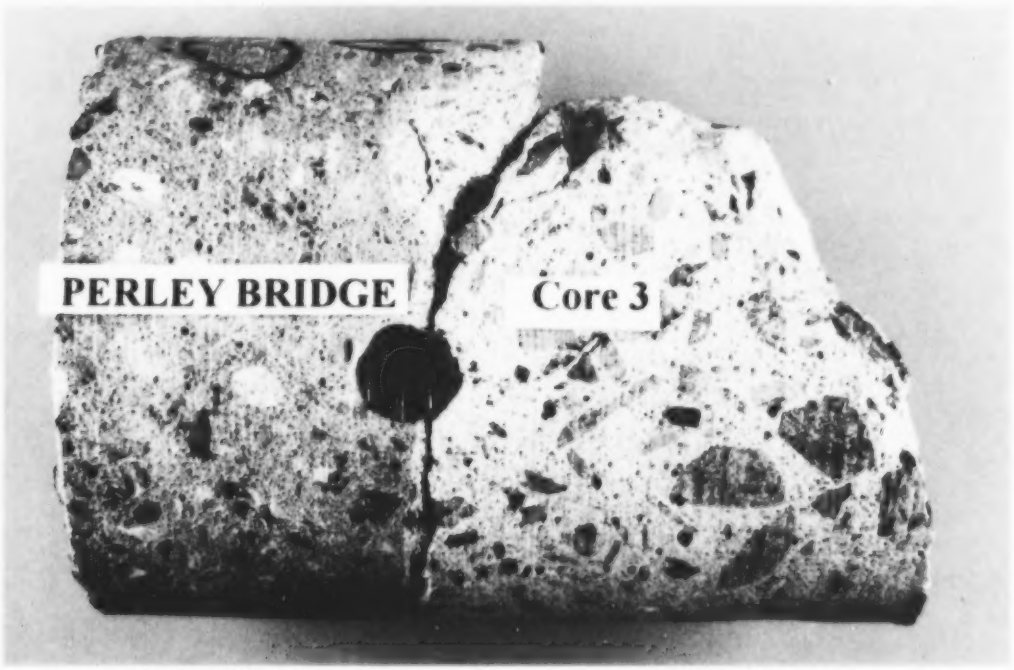

Figure 8 Core showing delamination, Perley Bridge, 1998

Figure 9 Core showing corrosion of ECR, Perley Bridge, 1998

Figure 10 Core showing delamination, Perley Bridge, 1998

Figure 11 Corrosion of ECR, Perley Bridge, 1998

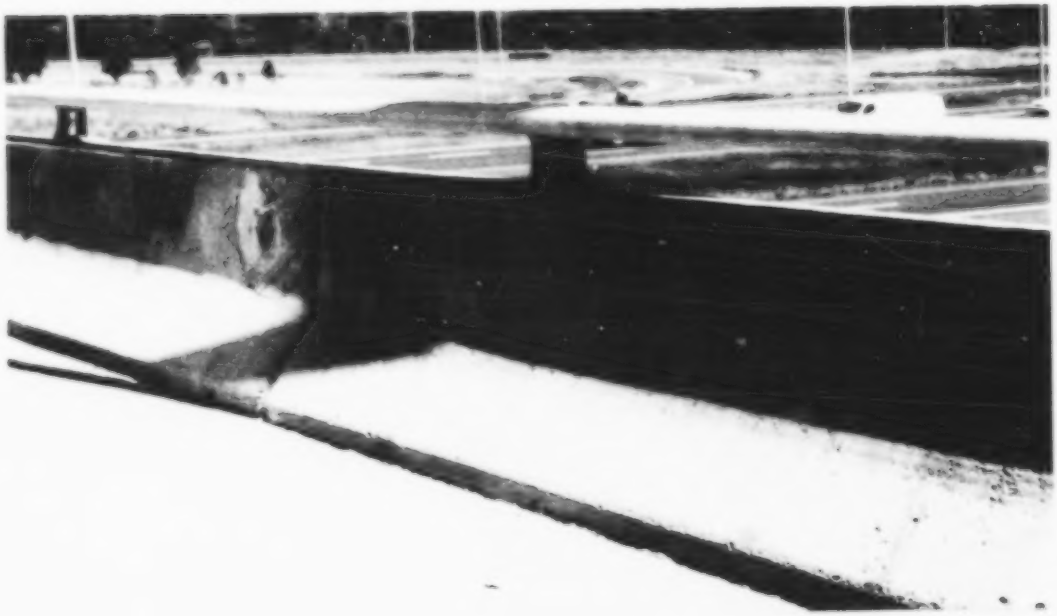

Figure 12 Corrosion-induced delamination, 1997, Eglinton Avenue (Site 24-319)

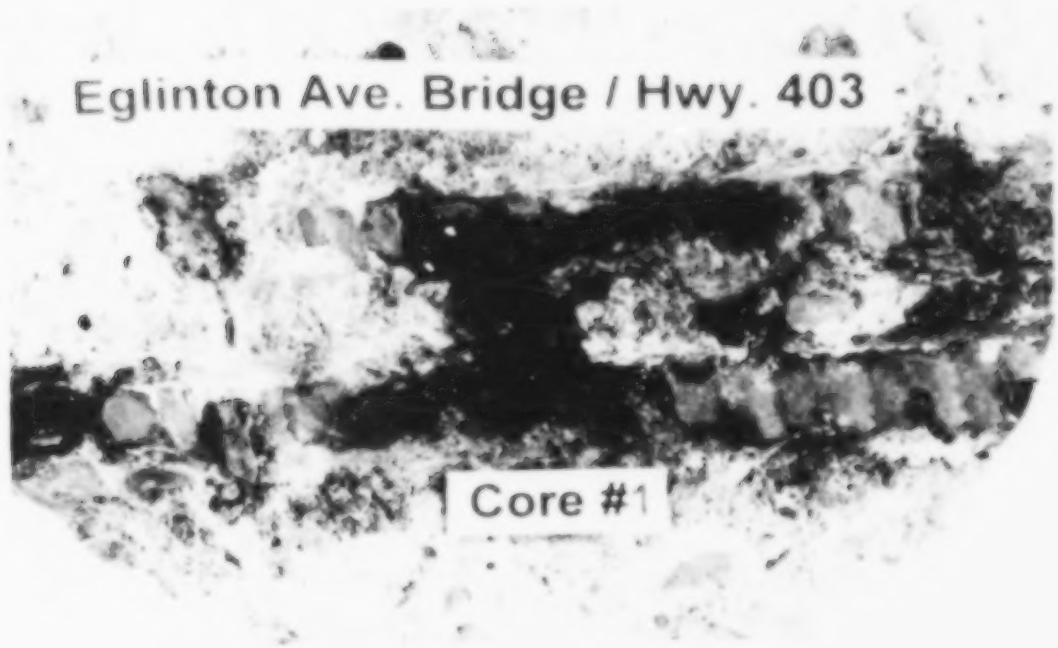

Figure 13 Corrosion Found in Core, 1997, Eglinton Avenue (Site 24-319)

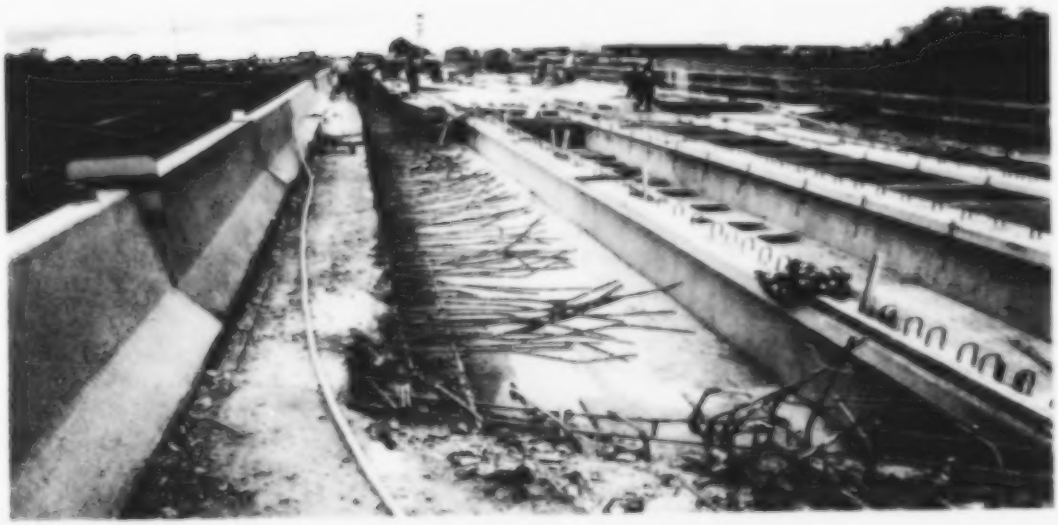

Figure 14 Overview of Humber River Bridge (Site 37-633), 1998

Figure 15 ECR exposed by construction operations, Humber River Bridge (Site 37-633)

Figure 16 ECR exposed by construction operations, Humber River Bridge (Site 37-633)

Figure 17 Poor condition of ECR, Humber River Bridge (Site 37-633)

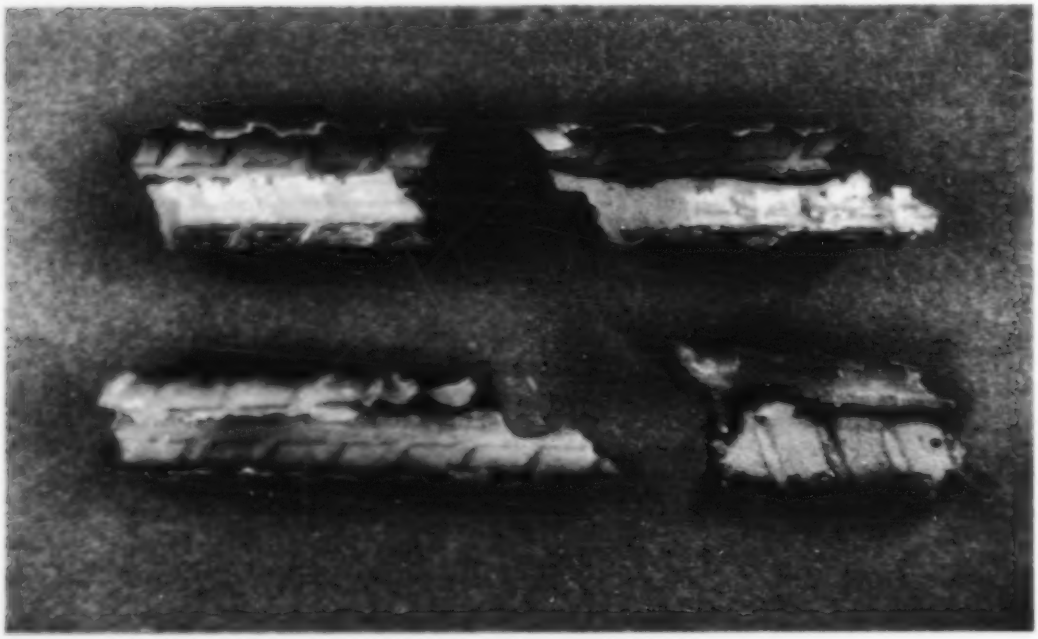

Figure 18 Condition of ECR, Garden City Skyway (Site 18-111), 2002

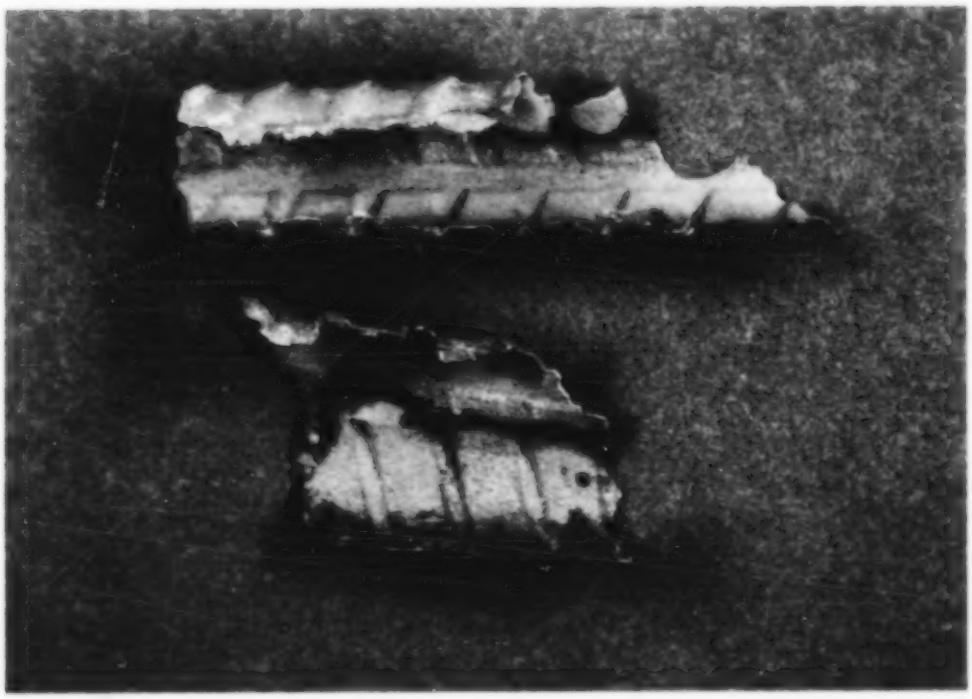

Figure 19 Condition of ECR, Garden City Skyway (Site 18-111), 2002

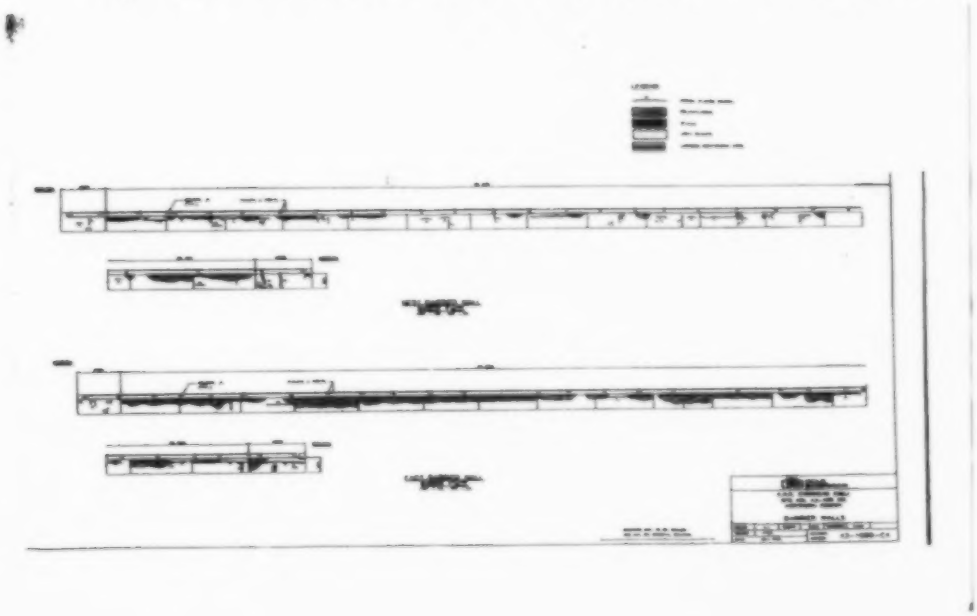

Figure 20 Drawing showing extent of delaminations at CNR Bridge (Site 43-105)

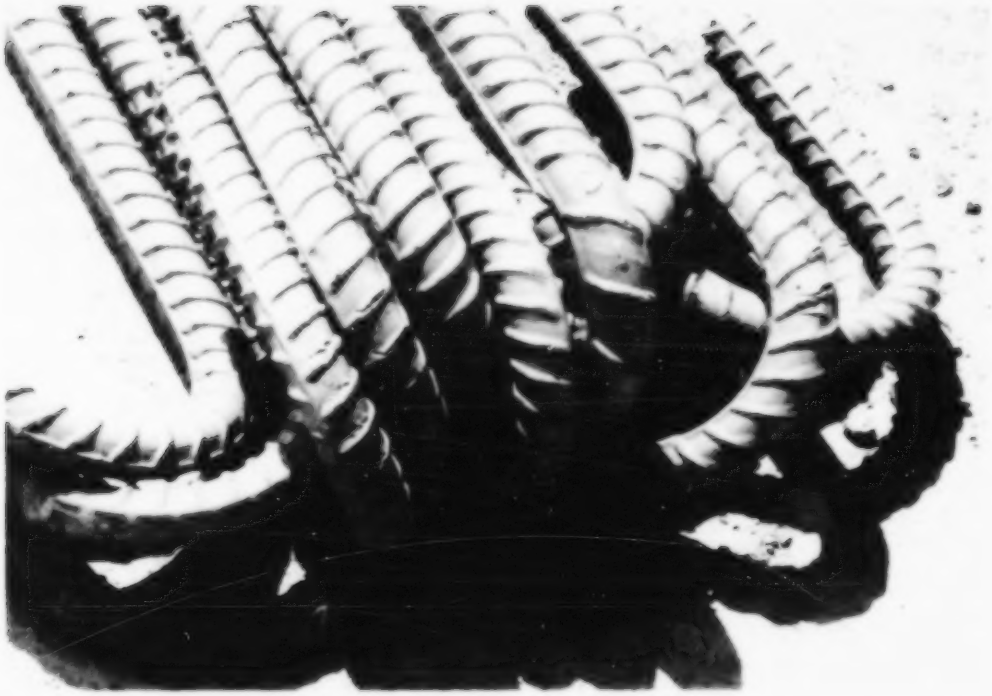

Figure 21 Example of Job Site Quality

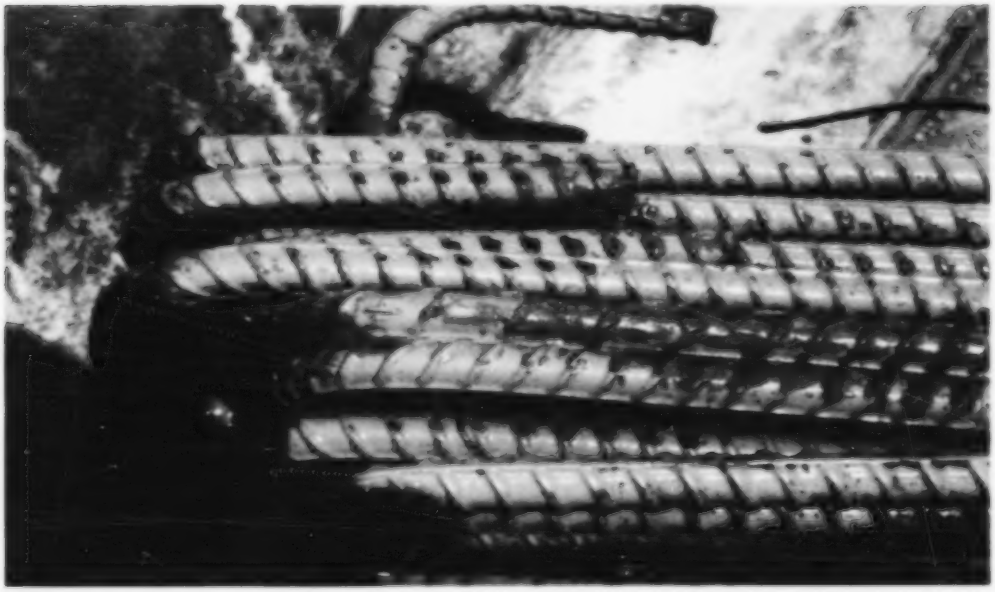

Figure 22 Example of Job Site Quality

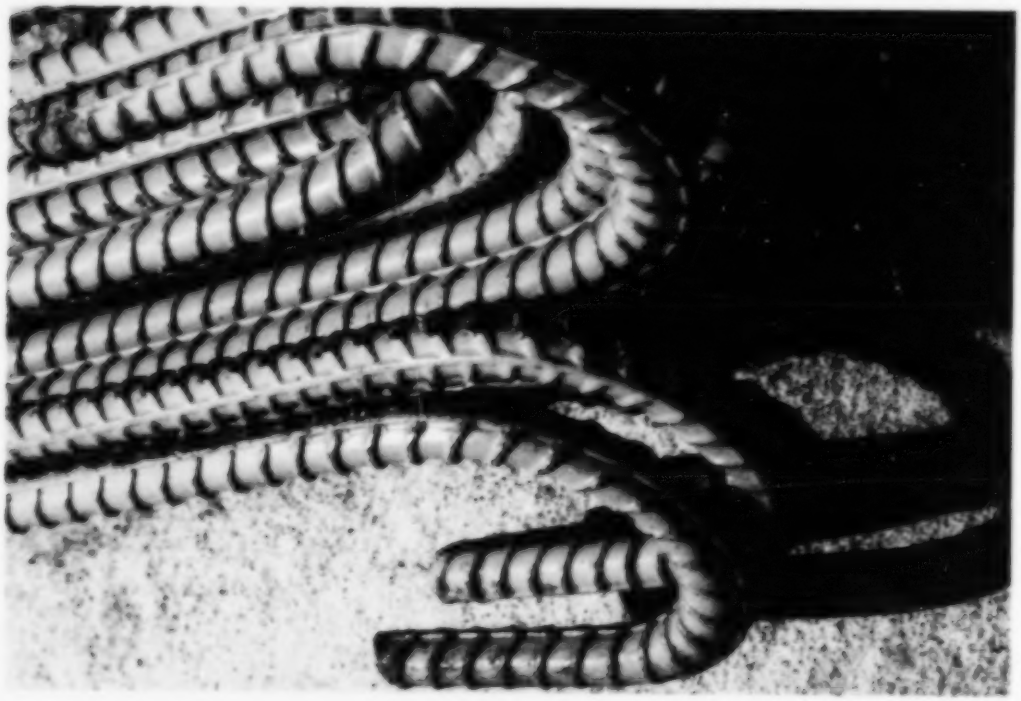

Figure 23 Example of Job Site Quality

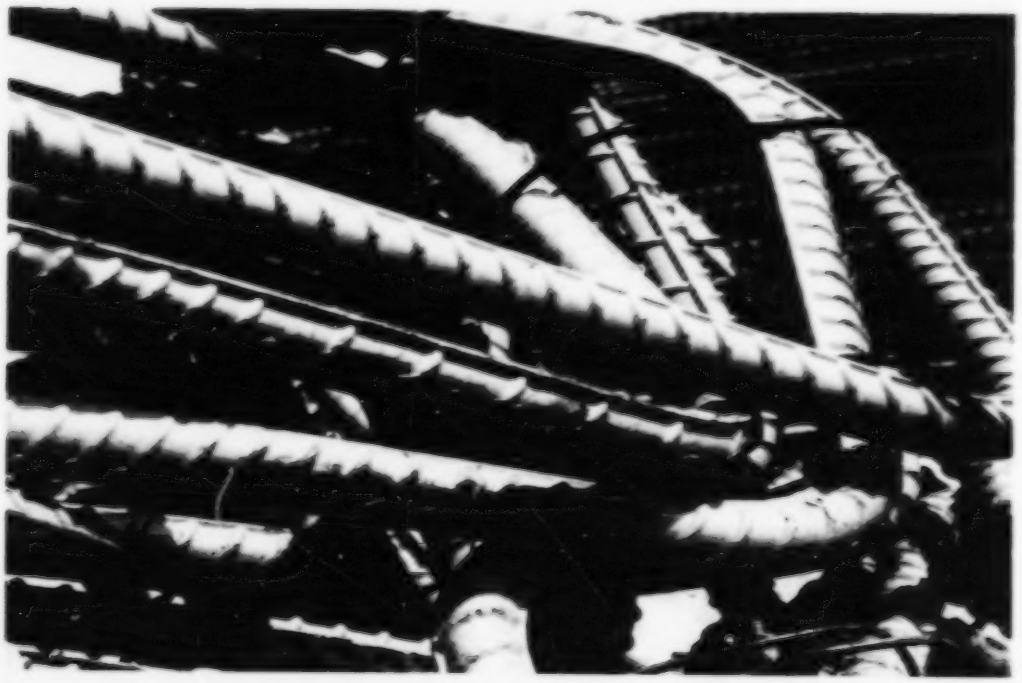

Figure 24 Example of Job Site Quality